

Thermoset material based on antiplasticized polythiourethane and ophthalmic lens comprising an antiplasticized thermoset material

The present invention relates generally to novel thermoset materials containing sulphur atoms and having an improved impact resistance, and also relates to optical articles, especially ophthalmic lenses made of thermoset materials that contain in particular sulphur atoms with a better impact resistance.

Research on novel polymer-based materials in order to produce said "organic" glasses is a constant matter of concern in the ophthalmic field.

For these materials to be applied in the ophthalmic field, they not only have to be transparent of course, but they also must have a high refractive index (n_D^{25}), so as to reduce the glass thickness, as well as very good mechanical properties, especially with regard to the impact and scratch resistance.

High refractive index classical materials used in ophthalmic optics are thermoset plastic materials based on polythiourethane. These materials may have refractive indices (n_D^{25}) of 1.67 or above.

However, such thermoset materials based on polythiourethane have a poor impact resistance, especially as compared to a material such as polycarbonate ($n_D^{25} = 1.59$). These thermoset materials based on polythiourethane are produced by polyaddition of polythiols and polyisocyanates. Their brittleness results from the high cross link density needed for obtaining thermal properties sufficient for an ophthalmic application.

As opposed to polycarbonate, (thermoplastic), they are on the other hand substantially more solvent resistant.

Therefore, it would be desirable to improve the impact resistance properties of these materials while preserving their intrinsic properties.

Generally speaking, a number of methods have been developed and studied so as to improve polymer matrix breaking strength and impact resistance. Known solutions, for both thermoplastic and thermoset materials provide for a second, more flexible phase. Such phase acts as a stress concentrator within the material, and enables the triaxial stress state

to be relaxed (through cavitation or plasticity development), slows down the crack propagation rate (crack deviation, multiple crack formation) and facilitates the shear strain within the lattice.

The phase separation may be obtained during polymerization, by
5 combining different types of monomers or prepolymers inducing soft segments and rigid segments.

During the polymer preparation, some arrangement get organized based on the difference of affinity between such segments. Depending on the selected monomers, segregation may be more or less marked.

10 While this method often applies to linear segmented polymer formation (thermoplastic polymers) it also may be used for crosslinked polymers.

The reaction generally proceeds in two steps. In the first step a long chain -containing soft prepolymer is formed, then rigid segments are
15 integrated, the viscosity having been optionally adjusted in the meantime by adding monomers. The crucial parameter for the morphology evolution is the second reactant solubility in the prepolymer and the evolution thereof during the chain growth.

Many studies have been conducted on polyurethanes and
20 polyurethane/urea hybrids.

Studies on epoxy lattices have demonstrated an increase in the impact resistance in presence of anti-plasticizing and damping additives. Recent studies (Sauvant V; Halary J.L; J.Appl. Polym. Sci; 82, 759 (2001) and Sauvant V; Halary J.L; Composite Sci and Tech; 62, 481
25 (2002)) showed indeed that with epoxy lattices, a phase separation may be obtained while retaining the antiplasticized character of the material. The material morphology is that of a nanocomposite, with additive molecule aggregates dispersed within a matrix plasticized by residual molecules.

30 With 15% by weight of antiplasticizing additives providing a damping effect, the storage modulus E' at 25°C was thus increased by 1.3 and the energy release ratio G_{IC} by 5. Moreover, moisture uptake was reduced. It will be appreciated that with a non damping antiplasticizer, the increase in the modulus is identical, but that the toughness rise is very
35 limited. Indeed, the drop in glass transition temperature makes it possible

for the antiplasticized material to be more resistant than the pure matrix, but not to such an extent as with the damped antiplasticized material.

The American patent US-4,348,497 describes thermosetting acrylic compositions comprising as antiplasticizer a tetrabenzoate
5 pentaerythritol. The antiplasticizer improves hardness and resistance to solvents. The material is used for producing coatings.

The American patent US-5,512,376 describes vinyl/SiH compositions comprising an antiplasticizer incorporated into the polymerizable composition prior to polymerizing.

10 It is thus an object of the present invention to provide thermoset materials containing sulphur atoms, preferably comprising a polythiourethane matrix or resulting from the polymerization of at least one polyepisulfide, in particular a diepisulfide, and having an improved impact resistance.

15 It is another object of the present invention to provide an ophthalmic lens comprising an optically transparent thermoset matrix, especially containing sulphur atoms, preferably a polythiourethane matrix or resulting from the polymerization of at least one polyepisulfide, in particular a diepisulfide, having an improved impact resistance.

20 According to the present invention, the hereabove objectives are achieved by adding to the thermoset matrix, especially a polythiourethane matrix, at least one molecule that does not react with the matrix and that imparts to said matrix antiplasticizing and preferably also damping properties.

25

Definitions

Antiplasticization

Introducing a small, non reactive molecule into a polymer results in the plasticization of the material that is characterized by a drop in glass
30 transition temperature (T_g), as well as by a decrease in the storage modulus as compared to the pure material. The additive is then called plasticizer. The antiplasticization as evidenced by Jackson and Caldwell (Jackson W. J., Caldwell J.R, J.Appl. Polym. Sci, 11, 211 (1967), Jackson W.J., Caldwell J.R, J.Appl. Polym. Sci, 11, 227 (1967)) does also express
35 as a decrease in the glass transition temperature, but differentiates itself

from plasticization in that the storage modulus increases in a temperature range that is generally close to the ambient temperature. In that case, the additive is called antiplasticizer.

This particularity is due to a strong attenuation of a significant secondary transition, close to the ambient temperature, but the fact that a secondary transition does exist involves a drop in the storage modulus. The transition attenuation causes the modulus decrease to disappear in this temperature range. Thus, the plasticizing effect of the molecule on the material modulus is hindered in the temperature range that is affected by the secondary transition attenuation: the material is antiplasticized.

A good affinity between the additive and the polymer is necessary for the antiplasticization. This is often achieved by using an additive the chemical structure of which is close to that of the matrix.

The molecular origin of this phenomenon has been explained only recently. It comes from an immobilization caused by the additive molecules of the movements that are responsible for the secondary transition, at the movement propagation points.

Damping

Damping reflects the reinforcement of the impact resistance toughness resulting from a phase separation within the material. Obtaining antiplasticization together with damping implies the selection of an additive with particular solubility properties. It must be fully miscible with the monomers, while immiscible with the polymer formed.

The phase separation occurs during the polymerization.

As defined herein the phase separation means at least one new phase being created in the form of domains, the largest size of which is less or equal to 10 micrometers and the antiplasticizing additive content of which is higher than that of the three-dimensional polymer matrix remainder.

Preferably, the maximal size of such domains is less than 500 nm.

More preferably, the maximal size of such domains is less than 50 nm. In the later case, it has to be considered by definition as being a nanophase separation.

Most preferably, the maximal size of such domains is less than or equal to 20 nm.

According to a first aspect, the present invention provides a thermoset plastic material having a three-dimensional matrix containing sulphur atoms, preferably a polythiourethane matrix or a polyepisulfide matrix, and at least one antiplasticizing additive which is unreactive with said matrix, and preferably selected so as to produce a nanophase separation within the final thermoset material.

According to a second aspect, the present invention provides an ophthalmic lens made of an optically transparent, thermoset plastic material, comprising a three-dimensional polymer matrix, the loss modulus (E'') of which has a secondary glass transition (β), especially of polythiourethane, and at least one antiplasticizing additive, which is unreactive with said matrix polymer and preferably producing a nanophase separation within the final thermoset plastic material.

Antiplasticized thermoset materials according to the invention preferably have an energy release ratio G_{IC} above 0.15 kJ.m^{-2} and more preferably of 0.20 or more.

Antiplasticizers according to the invention have an antiplasticization temperature range generally ranging from 0 to 85°C .

As previously stated, antiplasticizing additives generally have a solubility parameter (δ_a) relatively close to that of the monomers previously used to form the matrix so as to be miscible in the latter, but preferably sufficiently different from that of the formed matrix so that a phase separation can occur.

In general the solubility parameter δ does satisfy the following relation:

$$\delta_{mo} - \delta_a < 5 \text{ MPa}^{1/2}$$

wherein δ_{mo} corresponds to the solubility parameter of the monomers previously used for producing the matrix, especially polyisocyanates and polythiols as far as a polythiourethane matrix is concerned.

Also preferably the solubility parameter δ does satisfy following relation:

$$\delta_{ma} - \delta_a > 4 \text{ MPa}^{1/2},$$

wherein δ_{ma} corresponds to the solubility parameter of the matrix.

The antiplasticizing additive generally has a solubility parameter satisfying the following relation:

$$19 \leq \delta_a \leq 23.$$

5 The additivity law used to calculate solubility parameters δ ($\text{MPa}^{1/2}$) is as follows:

$$\delta = \left(\frac{-\sum_z {}^z\Delta U}{\sum_z {}^zV} \right)^{\frac{1}{2}}, \text{ where } {}^z\Delta U: \text{ molar vaporization energy and } {}^zV: \text{ molar}$$

10 volume.

There are several classifications (Hoy, Fedors, Bondi, ...). Fedors tables have been chosen as the most frequent values in "Handbook of Solubility Parameters" (Barton A.F.M., Handbook of Solubility Parameters, CRC Press, Boca Raton (1991)) were provided by this

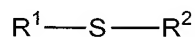
15

author. Antiplasticizing additives suitable for the present invention may be selected from dialkyl sulfides, diaryl sulfides, dialkylaryl sulfides, alkylaryl sulfides, arylalkylaryl sulfides, aryl and alkyl silane sulfides, carbonyl derivatives, S-arylthioalkylates, bis-arylthioalkyls, thiourea

20

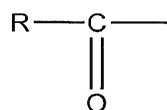
derivatives, urethane derivatives, diurethane derivatives and mixtures thereof. A first class of antiplasticizing additives includes thioethers of formula:

25



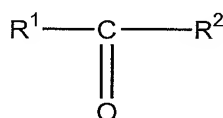
30

wherein R^1 and R^2 , being the same or different, represent independently from each other an alkyl radical, preferably a $\text{C}_1\text{--C}_{12}$ alkyl radical, more preferably a $\text{C}_4\text{--C}_{10}$ alkyl radical, in particular an octyl radical; a cycloalkyl radical, preferably a 6-membered radical, such as a cyclohexyl radical; an aryl radical such as a phenyl radical; an arylalkyl radical such as a benzyl radical; a radical



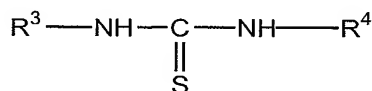
wherein R is an alkyl radical, preferably a C₁-C₆ alkyl radical such as methyl, ethyl, propyl; a trialkyl silane radical, especially a trimethyl silane.

A second class of antiplasticizing additives includes carbonyl derivatives of formula:



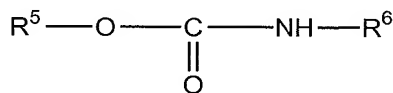
wherein R¹ and R² are such as previously defined.

A third class includes thioureas of formula:



wherein R³ and R⁴, being the same or different, represent independently from each other an alkyl radical, preferably a C₁-C₁₂ alkyl radical, more preferably a C₄-C₁₀ alkyl radical, a cycloalkyl radical, preferably a 6-membered radical such as a cyclohexyl radical; an alkyl radical bearing a nitrogen and/or an oxygen heterocycle such as a 4-morpholinoalkyl radical, especially a 4-morpholinoethyl radical.

A fourth class of antiplasticizing additives includes urethanes of formula:



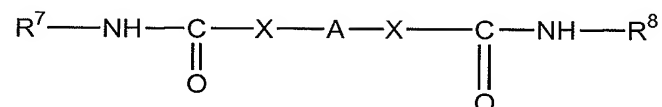
wherein R⁵ and R⁶, being the same or different, represent independently from each other a cycloalkyl group, preferably a 6-membered radical, such as a cyclohexyl radical; a cycloalkyl alkyl group such as a cyclohexylalkyl group, in particular a cyclohexylpropyl group;

an aryl group such as a phenyl group; an arylalkyl group in particular a phenylpropyl group.

A fifth class of antiplasticizing additives includes diurethanes.

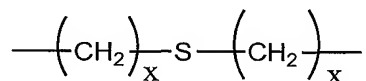
A first group of diurethanes includes those of formula:

5

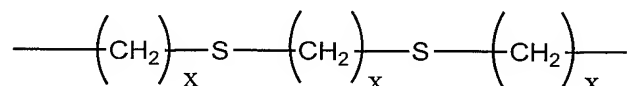


wherein A represents a C₁-C₁₂ alkylene group, preferably a C₆-C₁₀ alkylene group, in particular an octylene group, a group:

10



or:

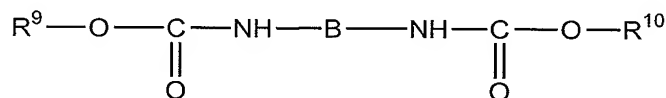


15

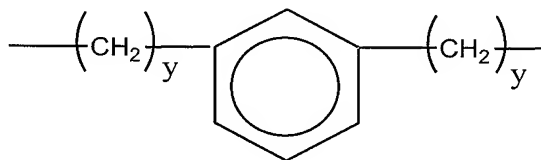
wherein x is an integer ranging from 1 to 6, preferably x is 2; X represents -O- or -S-; and R⁷ and R⁸ represent independently from each other, a cycloalkyl group, preferably a 6-membered group, in particular a cyclohexyl group, or an aryl group, preferably a 6-membered group, in particular a phenyl group.

A second group of diurethanes includes diurethanes of formula:

20

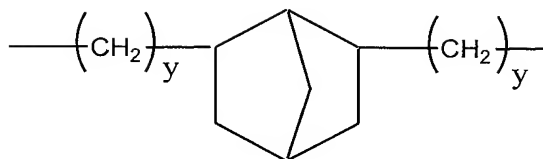


wherein B represents a radical of formula:



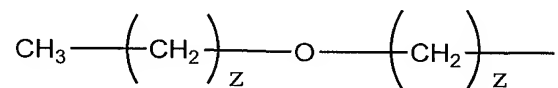
25

or



wherein y is an integer ranging from 1 to 4, preferably y is 1, and R⁹ and R¹⁰ represent independently from each other, a cycloalkyl-alkyl radical, in particular a cyclohexyl(C₁-C₆)alkyl radical such as a cyclohexylethyl or cyclohexylpropyl radical; an aryl(C₁-C₆)alkyl radical, in particular a phenylpropyl radical; a (bridged) cycloalkyl (C₁-C₆)alkyl radical such as a norbornylmethyl radical; ether-oxide radicals of formula:

10

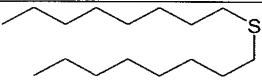
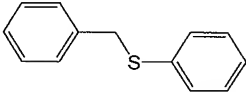
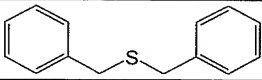
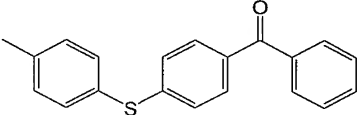
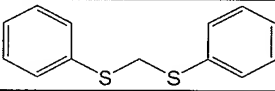
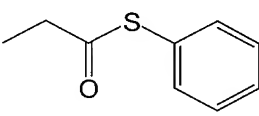
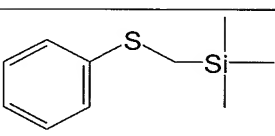
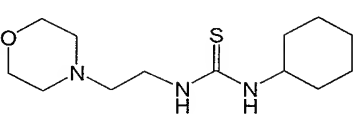


wherein z is an integer ranging from 1 to 4, preferably z is 2.

Amongst the preferred plasticizing additives are:

15

- Commercial additives,

Abbreviation	Name	Formula	δ_a MPa ^{1/2}	n _{GD}
os	Dioctyl sulfide		17.5	1.466
bps	Benzyl and phenyl sulfide		22.0	1.649
dbs	Dibenzyl sulfide		21.7	1.632
4ptbp	4-(p-tolylthio) benzophenone		23.8	1.728
bptm	bis(phenylthio)methane		23.0	1.689
sptp	S-phenylthiopropionate		21.9	1.555
ptm-tms	Phenylthiomethyl trimethyl silane		18.5	1.539
ch-me-tu	1-cyclohexyl-3-(2-morpholinoethyl)-2-thiourea		22.7	1.600

Abbreviation	Name	Formula	δ_a MPa ^{1/2}	n _{GD}
chp-ch-u	cyclohexylpropyl- cyclohexyl- urethane		19.7	1.509
pp-ch-u	phenylpropyl- cyclohexyl- urethane		20.9	1.558
Ch-ch-odu	cyclohexyl- cyclohexyl-(octane diurethane)		20.6	1.527
Chp-chp-xdu	cyclohexylpropyl- cyclohexylpropyl xylylene diurethane		21.1	1.566
che-che-xdu	cyclohexylethyl- cyclohexylethyl xylylene diurethane		21.4	1.573
pp-p-u	phenylpropyl- phenyl-urethane		22.4	1.634
pe-pe-xdu	propoxyethyl- propoxyethyl xylylene diurethane		21.5	1.556
nm-nm-xdu	norbornanemethyl- norbornanemethyl xylylene diurethane		22.3	1.615

pp-pp-xdu	phenylpropyl-phenylpropyl-xylylenediurethane		22.8	1.637
ch-ch-tdedSu	cyclohexyl-cyclohexyl-(thiodiethane di-S-thiourethane)		22.8	1.606
p-p-tdedSu	phenyl-phenyl-(thiodiethane di-S-thiourethane)		25.1	1.733
ch-ch-dtodu	cyclohexyl-cyclohexyl-(dithiaoctane diurethane)		22.0	1.578
p-p-dtodu	phenyl-phenyl-(dithiaoctane diurethane)		24.1	1.688
chp-chp-ndu	cyclohexylpropyl-cyclohexylpropyl dimethyl norbornane diurethane		20.5	1.546
che-che-ndu	cyclohexylethyl-cyclohexylethyl dimethyl norbornane diurethane		20.7	1.551
pe-pe-ndu	propoxyethyl-propoxyethyl dimethyl norbornane diurethane		20.7	1.532
nm-nm-ndu	norbornanemethyl-norbornanemethyl dimethyl		21.4	1.589

	norbornane diurethane			
pp-pp-ndu	phenylpropyl-phenylpropyl-dimethylnorbornane diurethane		22.0	1.610
ch-ch-tdedu	cyclohexyl-cyclohexyl-(thiodiethane diurethane)		21.8	1.563
p-p-tdedu	phenyl-phenyl-(thiodiethane diurethane)		24.2	1.689

Additive solubility parameters were calculated as previously stated and the refractive index was estimated according to the Blackstone and Dale method (1858): $n_{GD} = 1 + R_{GD} / V$.

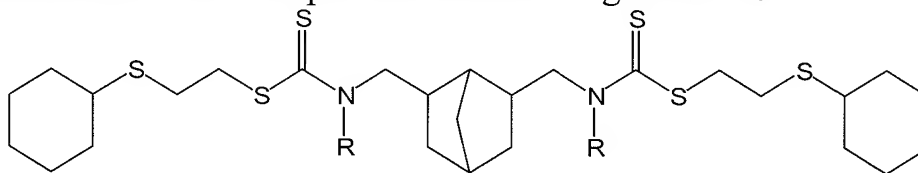
- 5 $R = \sum_i R_i$, where R_i is defined for each molecule constitutive group (Van Krevelen, D.W., Properties of Polymers, Elsevier (1990); V represents the molar volume.

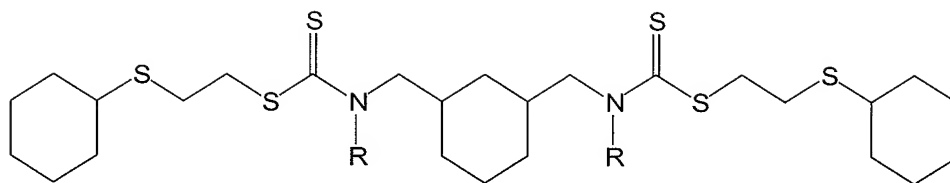
Synthesized additives were synthesized from thiols or from alcohols and isocyanates in suitable molar amounts.

- 10 If possible, the reaction is a high temperature bulk reaction.

When the melt temperature of the final compound needs an excessively high heating temperature to keep in a liquid state, a solvent will be preferably used together with an evaporation step.

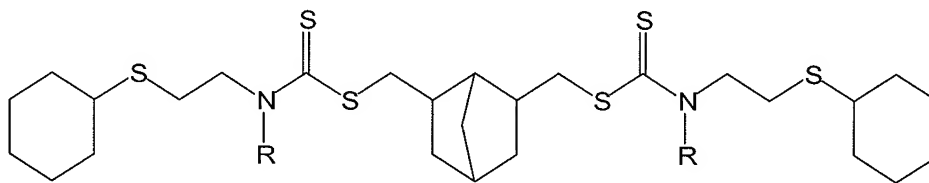
- 15 Antiplasticizing additives suitable for the present invention may also be selected from compounds of following formulas:



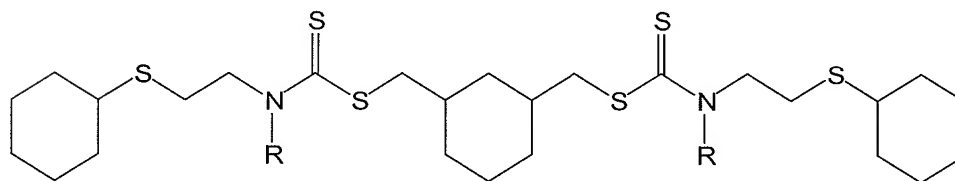


wherein R represents H, an alkyl group, especially, a methyl, ethyl, n-propyl or n-butyl group, or an aryl group, especially a phenyl group, or isomers thereof of formula:

5



or



10

wherein R represents H, an alkyl group, especially a methyl, ethyl, n-propyl or n-butyl group, or an aryl group, especially a phenyl group.

15 As an example, [bicyclo[2.2.1]heptane-2,6 carbamate (and 2,5)-diylbis(methylene)]bis[(2-ethandiyl)thio]cyclohexyl sulfide preparation is described hereunder.

A solution of carbon disulfide (25.04 g; 0.329 mol, 19.8 mL) and dry chloroform (120 mL) is added dropwise to a solution cooled at -5°C of bicyclo[2.2.1]heptane-2,6 (and 2,5)-dimethanamine (23.10 g; 0.150 mol; International Resources), triethylamine (30.26 g; 0.300 mol, 4.16 mL) and dry chloroform (240 mL), under nitrogen. The mixture is cooled at -5°C again, then a solution of [(2-bromoethyl)thio]cyclohexane (67.16 g; 0.300 mol) is added dropwise to dry chloroform (120 mL). The resulting reaction mixture is then warmed up to the ambient temperature, and kept under stirring at the same temperature for 18 hours.

25

The reaction mixture is then concentrated under vacuum and the residue is dissolved in ethyl acetate, and washed with aqueous hydrochloric acid (1.0 M) then with water. The ethyl acetate phase is separated, dried and submitted to evaporation to give
5 [bicyclo[2.2.1]heptane-2,6 carbamate (and 2,5)-
diylbis(methylene)]bis[(2-ethandiyl)thio]cyclohexyl sulfide as a pale yellow viscous oil. (88.39 g; yield 99.6%)

As an example, [1,3-cyclohexanediyl bis(methylene)]bis[(2-ethandiyl)thio]cyclohexyl sulfide carbamate preparation is described
10 hereunder.

A solution of carbon disulfide (11.76 g; 0.155 mol, 19.6 mL) and dry chloroform (120 mL) is added dropwise to a solution cooled at -5°C comprising 1,3-bis(aminoethyl) cyclohexane (10.03 g; 0.155 mol), triethyl amine (14.23 g; 0.141 mol, 19.6 mL) and dry chloroform
15 (120 mL), under nitrogen. The resulting reaction mixture is warmed up to the ambient temperature for one hour then kept under stirring for 1 hour.

The reaction mixture is then cooled at -5°C and treated dropwise with a solution of [(2-bromoethyl)thio]cyclohexane sulfide (34.5 g; 0.155 mol) in dry chloroform (60.0 mL). The reaction mixture is then
20 warmed up to the ambient temperature, then kept under stirring for 18 hours.

The reaction mixture is then concentrated under vacuum and the residue is dissolved in ethyl acetate, and washed with aqueous hydrochloric acid (1.0 M), then with water. The organic phase is
25 separated, dried and submitted to evaporation to give [1,3-cyclohexane diylbis(methylene)]bis[(2-ethandiyl)thio]cyclohexyl sulfide carbamate as a pale yellow viscous oil. (35.32 g; yield 86.8%)

The preparation of the cyclohexylpropyl cyclohexypropyl dimethyl norbornane diurethane additive (chp-chp-ndu) will now be described as
30 an example.

- Compounds

Name	weight (g)	mole number (mmol)
Cyclohexyl propanol (chp)	11.60	81.6
Dimethylnorbornyl diisocyanate (NDI)	8.40	40.7
(dibutyltin dichloride) catalyst	0.002	0.01% by weight

Procedure

5 Cyclohexyl propanol, dimethyl norbornyl diisocyanate and the catalyst are mixed together. The mixture is heated at 70°C and diisocyanate -characteristic peak disappearance is monitored by infrared spectroscopy (typical time = 2 hours). Heating is stopped and the product is conditioned under inert atmosphere (N₂ or Ar).

10 Generally, the antiplasticizing agent represents from 5 to 25% by weight as compared to the total weight of the polythiourethane matrix and more preferably from 5 to 15% by weight.

As previously stated, the thermoset plastic material according to the invention comprises a three-dimensional matrix containing sulphur
15 atoms.

Preferably, it is a polythiourethane matrix.

Another preferred thermoset plastic material is a polymer obtained by polymerizing a composition comprising at least one polyepisulfide, preferably a diepisulfide.

20 The polythiourethane three-dimensional matrix is obtained by polyaddition of at least one polyisocyanate, preferably a diisocyanate, and of at least one polythiol, preferably a tri- or tetrathiol.

Polyisocyanates are generally aromatic polyisocyanates, aliphatic and cycloaliphatic polyisocyanates and mixtures thereof.

25 Preferably, di- or triisocyanates will be used, even more preferably diisocyanates.

Aromatic polyisocyanates include for example phenylene diisocyanate, ethylphenylene diisocyanate, isopropylphenylene

diisocyanate, dimethylphenylene diisocyanate, diethylphenylene diisocyanate, diisopropylphenylene diisocyanate, trimethylbenzyl triisocyanate, xylylene diisocyanate (XDI), benzyl triisocyanate, 4,4'-diphenylmethane diisocyanate and isophorone diisocyanate.

5 Aliphatic polyisocyanates include for example hexamethylene diisocyanate.

Cycloaliphatic polyisocyanates include for example bis(isocyanate)methyl cyclohexane, dicyclohexyl methane diisocyanate, dimethyl norbornyl diisocyanate (NDI) and norbornyl methyl
10 diisocyanate.

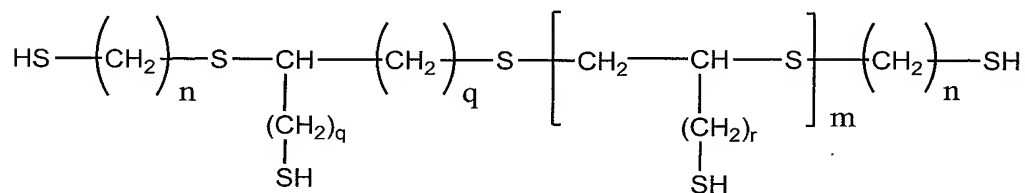
Of course mixtures of such diisocyanates may be used. The preferred diisocyanate mixture comprises a combination of xylylene diisocyanate (XDI) and dimethyl norbornyl diisocyanate (NDI), especially a 50:50 mixture (w/w).

15 Polythiol monomers may have following formula:



wherein R' is an organic group the valence of which corresponds to
20 n'; n' being an integer ranging from 2 to 6, preferably being 3 or 4.

A preferred polythiol class includes polythiols of formula:

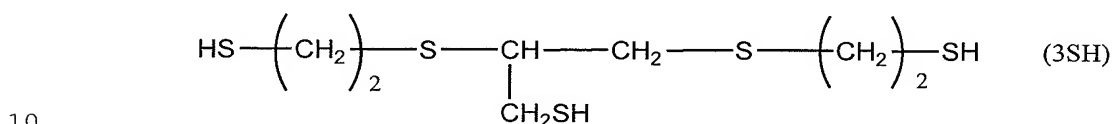


wherein n is an integer ranging from 1 to 4, preferably n is 2, p, q
25 and r are integers ranging from 1 to 4, preferably 1, and m is 1 or 2.

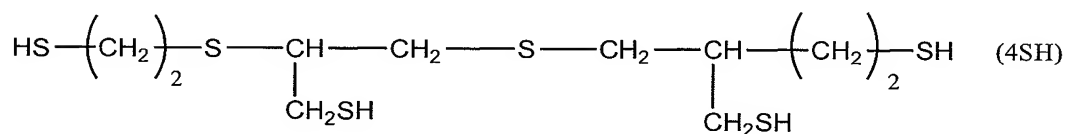
Preferred polythiol monomers include for example aliphatic polythiols such as pentaerythritol tetrakis mercaptopropionate, 1-(1'-mercaptoethylthio)-2,3-dimercaptopropane, 1-(2'-mercaptoethylthio)-2,3-dimercaptopropane, 1-(3'-mercaptoethylthio)-2,3-dimercaptopropane, 1-(4'-mercaptoethylthio)-2,3-dimercaptopropane, 1-(5'-mercaptoethylthio)-2,3-dimercaptopropane, 1-(6'-mercaptoethylthio)-2,3-dimercaptopropane, 1,2-bis(4'-

mercaptobutylthio)-3,mercaptopropane, 1,2-bis(6'-mercaptohexyl)-3-mercaptopropane, 1,2,3-tris(mercaptomethyl thio)propane, 1,2,3-tris(3'-mercaptopropylthio)propane, 1,2,3-tris(2'-mercaptoethylthio)propane, 1,2,3-tris-(4'-mercaptobutylthio)propane, 1,2,3-tris(6'-mercaptohexylthio)propane, 1,6-hexanethiol-1,2,3-propanetritiol and 1,2-bis(2'-mercaptoethylthio)-3-mercaptopropane.

Preferred polythiols include 3-(2-sulfanylethylthio)-2-(2-sulfanylethylthio)propane-1-thiol of formula:



and tetrathiol of formula:



Polythiourethane matrices according to the invention may also be prepared from polythiourethane prepolymers having isocyanate and thiol end groups.

Preferred isocyanate end group-containing prepolymers have a number average molecular weight ranging from 1000 to 2000, preferably ranging from 1300 to 1700, and a NCO/S_H ratio from 4:1 to 30:1, preferably of 6:1 or more, and typically of 8:1.

S_H end group-containing polythiourethanes preferably have a number average molecular weight ranging from 200 to 300 and a S_H/NCO ratio ranging from 4:1 to 30:1, preferably of 6:1 or more, and typically of 8:1.

Any classical catalyst may be used for catalyzing the polyaddition reaction of the polyisocyanates and polythiols to produce polythiourethane matrices according to the invention. Such catalysts include for example tertiary amines, such as triethyl amine, organometallic compounds such as dimethyltin dilaurate, dibutyltin

dilaurate and dibutyltin dichloride, alkaline metal salts, alkaline earth metals, transition metals and acid ammonium salts satisfying the condition $0.5 \leq \text{pKa} \leq 14$.

5 Cocatalysts or promoters may also be used such as N,N-dimethyl cyclohexyl amine and 1,4-diaza-bicyclo-[2,2,2]-octane to increase catalyst activity.

Alkaline metal salts include especially KSCN optionally in admixture with a donor compound, such as an acetonitrile, amine, sulphone, sulfoxide, triarylsulfoxide, nitro, ethyleneglycol ether, crown
10 ether and cryptate compound. Preferred donor compounds are crown ether and cryptands.

In a further aspect, the polyaddition reaction for producing the polythiourethane matrix is well known from those skilled in the art and occurs in classical conditions.

15 The present invention further relates to an ophthalmic lens comprising an optically transparent, thermoset plastic material, comprising a three-dimensional polymer matrix, the loss modulus (E'') of which presents a secondary glass transition (β), and at least one antiplasticizing additive, also preferably having a damping effect.

20 Preferably, the lens thermoset material does exhibit a nanophase separation, such as previously defined.

As already mentioned, the matrix may be any transparent three-dimensional polymer matrix, the loss modulus (E'') of which does exhibit a secondary glass transition (β).

25 Suitable three-dimensional polymer matrices include for example three-dimensional matrices containing sulphur atoms and in particular polythiourethane matrices as described hereabove, and matrices produced by polymerizing at least one polyepisulfide, especially a diepisulfide.

Antiplasticizing additives may be selected from additives such as
30 those previously described taking also into account the conditions, as well as the amounts, that have been previously mentioned.

Naturally, choosing the antiplasticizer will depend on the nature of the matrix and should be such that a final transparent material is produced.

In general, thermoset materials for the ophthalmic lenses according to the invention are materials having a high refractive index (n_D^{25}) i.e. an index of at least 1.54, more preferably 1.60 or more, and most preferably of 1.65 or more.

5 The rest of the description refers to the appended figures which represent, respectively:

Figure 1 is a graph illustrating the storage modulus E' and the loss modulus E'' by means of a dynamic mechanic analysis (DMA) of a pure polythiourethane XDI/50NDI/4SH matrix and of a polythiourethane
10 antiplasticized matrix according to the invention;

Figures 2 and 3 are graphs showing the storage modulus E' evolution vs. temperature for a pure polythiourethane matrix and of the antiplasticized matrix according to the invention with increasing concentrations of pp-ch-u antiplasticizer;

15 Figure 4 is a graph showing gel times for the XDI/00NDI/3SH matrix at 60°C, depending on catalyst levels;

Figure 5 is a graph showing standard and short cycles (starting at 60°C) used for the polyaddition reaction; and

20 Figure 6 is a graph showing the geometry of the 3 point-bend test specimen used in the fracture tests.

Following examples illustrate the present invention.

Nomenclature

25 In the following examples, a nomenclature was used to refer to the matrices: all matrices were named basing on a basic matrix produced only from xylylene diisocyanate and the compound 3SH in molar proportions 1eq NCO to 1eq SH (by weight NCO 52%, SH 48%) and hereafter referred to as:

XDI/00NDI/3SH,

30 The other matrices are referred to by indicating the NDI weight proportion that partly replaces the XDI and the 4SH polythiol that replaces the 3SH polythiol. Thus, the matrix called XDI/50NDI/4SH is one that is analogue to the basic matrix except that 50% by weight XDI were replaced with 50% by weight NDI and 4SH polythiol replaced 3SH
35 polythiol (SH molar eq.).

The nomenclature used for referring to compounds comprising the antiplasticizing additive is as follows:

Polymer + 1/N additive (X%), where polymer is the abbreviation for the matrix. Additive is the abbreviation for the additive.

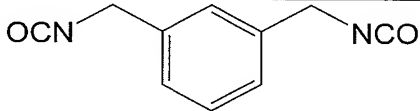
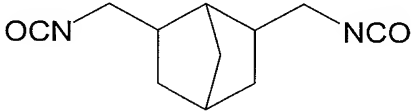
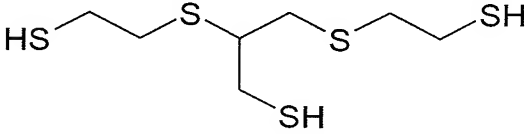
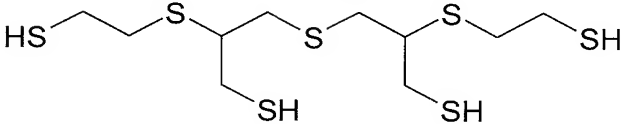
5 1/N is a fraction of the number of cross-linking points for an additive molecule.

X refers to the percentage by weight of additives.

10 Example: XDI/00NDI/3SH + 1/6dbs (6.17%): the matrix is the basic matrix with XDI and no NDI and with 3SH, to which dibenzyl sulfide (dbs) was added, in an amount of 1 mol additive for 6 cross-linking points, thus corresponding to 6.17% by weight.

Formulations

15 Formulations of the matrices containing various additives in different concentrations (up to 20% by weight) were prepared from following raw materials:

Compound name	Formula	δ_{mo} (MPa ^{1/2})
Xylylene diisocyanate (XDI)		25.3
Dimethyl norbornyl diisocyanate (NDI)		23.4
Trithiol (3SH)		22.7
Tetrathiol (4SH)		23.1

The polythiourethane matrices used are:

Compound	δ_{ma} (MPa ^{1/2})
XDI/00NDI/3SH	26.9
XDI/50NDI/4SH	26.3

General procedure

Heating was often necessary for dissolving additives in the monomers (up to 120°C for some additives). Except the solubility parameter, the melt temperature of the additives (or their glass transition temperature T_g , as measured by means of a differential scanning calorimetry (DSC), after

5 hardening) has an influence on the additive solubility. The solubility will be especially high since δ_a and T_f (additive melt temperature, as measured by DSC) or T_g are low, the isocyanate being a quite better solvent as compared with thiols, and so as to let the additive dissolve itself to

10 prevent the formulation from caking.

Formulations were treated according to following procedure steps consisting in:

1. Mixing the additive together with the isocyanate, upon heating if needed.
- 15 2. Adding the thiol, then mixing.
3. Optimizing the solubilization temperature.
4. Hot degassing.
5. Adding catalyst and internal mold release agent, quickly degassing.
6. Filling and starting polymerization cycle.

20 First assays were conducted with the XDI/00NDI/3SH matrix. However, the pure matrix glass transition temperature is already relatively low for the ophthalmic application. Since the presence of an additive causes the glass transition temperature to decrease, the use of the XDI/50NDI/4SH matrix (which T_g is 20°C higher than that of

25 XDI/00NDI/3SH) was subsequently preferred.

Detailed formulation example

Formulation with an additive: XDI/50NDI/4SH + 14% chp-chp-ndu

Name	Weight (g)	Number of moles (mmol)
xylylene diisocyanate (xdi)	4.03	21.4
dimethylnorbornyl diisocyanate (ndi)	4.03	19.6
tetrathiol (4sh)	7.94	20.5
release agent (Zelec UN)	0.02	0.1% by weight
catalyst (dibutyltin dichloride)	0.02	0.1% by weight
chp-chp-ndu additive	2.56	14% by weight

The additive was added to the isocyanate mixture (XDI + NDI). The mixture was heated at 60°C and stirred in order to dissolve the additive. Once the additive was dissolved, the mixture was let cool down to the ambient temperature (T_{amb}).

The thiol (4SH) was added.

Mixing at T_{amb} was performed, then a degassing step under vacuum was performed for about 45 min so as to remove bubbles.

The mold release agent and the catalyst were added. Stirring was performed.

The formulation was filtered (filter 1.2 μ m) and degassed under vacuum for 10 minutes.

The formulation was heated at 60°C while stirring for 5 minutes.

Moulds previously pre-heated at 60°C were filled.

The moulds were placed in an oven, cycle was started: for 2h increase in temperature from 60°C to 120°C; for 2h hold at 120°C; for 2h decrease in temperature from 120° to 50°C. Wait at 50°C.

The moulds were disassembled.

Formulations and results are given in tables I, II and III hereafter:

TABLE I

Formulations in the XDI/50NDI/4SH matrix

Additives	δ (MPa ^{1/2})	theoretical n	Amount (%)	Aspect	Antiplasticization extent	DMA new phase detection	T _g (max tan δ) °C	E' 25°C MPa	E' 100°C MPa	G _{ic} (kJ.m ⁻²)	K _{ic} 1/2 MPa.m ^{1/2}
Pure matrix											
dbs	21.7	1.632	12	transparent, irregular surface	-	-	115	4380	1870	0.12	0.64
bptm	23.0	1.689	20	transparent, irregular surface	medium	-	-	3320	15	-	-
chp-ch-u	19.7	1.509	8	Weakly diffusing	medium	No	106	4200	150	0.15	0.67
pp-ch-u	20.9	1.558	8	Transparent	medium	No	98	4450	72	-	-
			10	Transparent	high	No	86	4440	45	0.14	0.73
pp-p-u	22.4	1.634	8	Transparent	medium	No	96	4590	44	-	-
			10	Transparent	high	No	86	4600	21	0.15	0.72
chp-chp-xdu	21.1	1.566	10	Very weakly diffusing	medium	No	104	4330	170	-	-
			17	Strongly diffusing	high	Yes	100	3630	58	0.24	0.86
che-che-xdu	21.4	1.573	16	Transparent	high	No	95	4100	29	-	-
pe-pe-xdu	21.5	1.556	5	Transparent	medium	No	96	4490	45	-	-
			21	Transparent	medium	No	70	4190	16	0.29	0.96
nm-nm-xdu	22.3	1.615	19	Transparent	medium	No	96	4390	27	-	-
pp-pp-xdu	22.8	1.637	19	Transparent	medium	No	88	4300	17	-	-
chp-chp-ndu	20.5	1.546	10	Very weakly diffusing	medium	No	105	4150	170	-	-
			14	Weakly diffusing	medium	Yes	104	3850	77	0.43	1.15
che-che-ndu	20.7	1.551	17	Weakly diffusing	medium	Yes, quite clear	104	3110	157	1.76	1.82
			23	Transparent, irregular surface	medium	No	96	4000	22	-	-
pe-pe-ndu	20.7	1.532	5	Transparent	high	Yes, quite clear	96	3530	25	-	-
			21	Transparent	medium	No	98	4330	47	-	-
nm-nm-ndu	21.4	1.589	10	Transparent	medium	No	78	4390	15	0.18	0.73
			19	Weakly diffusing	high	No	102	4190	92	-	-
pp-pp-ndu	22	1.610	20	Transparent	high	No	100	4190	36	0.15	0.71
ch-ch-tdedu	0.8	1.563	10	transparent, slightly yellow	medium	No	88	4390	17	-	-
p-p-tdedu	24.2	1.689	10	transparent, slightly yellow	high	Yes	102	4110	99	0.17	0.76
			16	Transparent, yellow	high	No	99	4620	55	-	-
ch-ch-tdedSu	22.8	1.606	6	strongly diffusing	low	No	92	4700	23	-	-
p-p-tdedSu	25.1	1.733	6	strongly diffusing	very low	No	104	4430	108	-	-
ch-ch-dtodu	22.0	1.578	16	Weakly diffusing	medium	No	108	4240	203	-	-
p-p-dtodu	24.1	1.688	16	Weakly diffusing	high	No	92	4360	26	-	-
						No	88	4270	14	-	-

- means no measurement

TABLE II

Formulations in the XDI/00NDI/3SH matrix

Additives	δ (MPa ^{1/2})	theoretical n	Amount (%)	Aspect	Antiplasticization extent	DMA new phase detection	T _g (max tan δ) °C	E' 25°C MPa	E' 100°C MPa	G _{ic} (kJ.m ⁻²)	K _{ic} MPa.m ^{1/2}
pure matrix	-	-	-	-	-	No	94	4580	20	0.19	0.80
dbs	21.7	1.632	6	Transparent	Medium	No	76	4610	17	0.21	0.84
			9	Irregular surface	High	No	72	4450	17	-	-
			21	Opaque	-	No	-	-	-	-	-
chp-ch-u	19.7	1.509	3	Transparent	very low	No	90	4550	19	0.15	0.73
pp-ch-u	20.9	1.558	6	Transparent	medium	No	82	4100	15	-	-
			11	Transparent	medium	No	74	4590	15	0.22	0.88
			19	Irregular surface	medium	No	64	4000	12	-	-
pp-p-u	22.4	1.634	6	Transparent	high	No	82	4440	16	-	-
			11	Transparent	high	No	74	4840	16	0.24	0.89
			5	Transparent	none	No	84	4630	17	-	-
pe-pe-xdu	21.5	1.556	20	Irregular surface	high	No	66	4020	7	-	-
nm-nm-xdu	22.3	1.615	9	Transparent	low	No	84	4600	15	-	-
			5	Irregular surface	low	No	90	4370	17	-	-
			5	Transparent	none	No	88	4350	16	-	-
pe-pe-ndu	20.7	1.532	20	Transparent	medium	No	62	4490	12	-	-

Antiplasticization detection

The prepared samples were analyzed by several measuring devices so as to detect the antiplasticization.

Characterization

DMA viscoelasticity measurements make it possible to detect antiplasticization. β transition attenuation indeed immediately appears on $E''=f(T)$ plotting.

The method that was adopted to select additives seems to show consistency with the obtained results. The extent of such phenomenon nevertheless does vary from one compound to another. With a constant amount, the additives having the most important influence are those which solubility parameters are the highest. This may be due to a stronger affinity with the chains of the matrix, and thus a better blocking of the movement propagation points responsible for β transition.

Antiplasticization therefore does not necessarily show any rise in the E' modulus. Indeed, when the antiplasticizing effect is low, it is insufficient to balance the decrease in the modulus due to the additive being present.

The best systems do increase the E' modulus in a proportion amounting 0,6 GPa maximum, i.e. a 15% increase as compared to the XDI/50NDI/4SH pure matrix modulus which is around 4 GPa, as can be observed in the hereunder table and in figure 1.

Additive	δ (MPa ^{1/2})	Amount	Antiplasticizer temperature range	Maximum increase in E'
p-p-tdedu	24.2	1/5 (15.9%)	0°C – 70°C	0.6 GPa
ch-ch-tdedu+ p-p-tdedu mixture	23.0	1/9 (9.6%)	10°C – 80°C	0.6 GPa
pp-p-u	21.9	1/4 (14.6%)	0°C – 55°C	0.4 GPa
		1/8 (7.7%)	10°C – 70°C	0.3 GPa
Dbs	21.7	1/6 (8.6%)	10°C – 60°C	0.2 GPa

The other additives are not so strongly antiplasticizing, but they all attenuate the β transition. This does not necessarily express as an increase in the modulus, although many of them do successfully balance the decrease in the modulus around 30°C.

5 Should the incorporation rate increase, two opposite phenomena take place.

On the one hand both the modulus in the non antiplasticized zone and the glass transition temperature are reduced because of the greater amount of additive. On the other hand the antiplasticizing effect in the β transition zone is stronger.

The additional decrease in the storage modulus may therefore be balanced by the antiplasticizing effect. However, this is no longer possible when the additive amount becomes excessively high.

Data analysis concerning the pp-ch-u additive proves it for
15 XDI/50NDI/4SH matrix (figures 2 and 3). 8 and 10% incorporation rates cause the maximum increase in the storage modulus, as compared to the pure matrix in a temperature range of from 20°C to 60°C. With a 15% incorporation rate, antiplasticization does just balance the modulus decrease around 30°C. With 21% of additive, the decrease in the modulus
20 is too strong to be balanced by antiplasticization.

Glass transition

The glass transition temperature of the mixtures is reduced as compared to the pure matrix. This results from the additive, which presence causes the polymer to plasticize.

25 Achieving damping: phase separation

Antiplasticization is obtained with most of the additives, and the phase separation during polymerization was clearly evidenced for the additives the most suitable for producing such phase separation.

Detection

30 A second phase may be evidenced in different ways.

When the second phase-characteristic scale is bigger than the crucial size, which depends on the index difference between matrix and additive, the material is diffusing and even to the point of opacity.

Dynamic mechanic analysis (DMA) makes it possible to detect such phase separation by showing a new glass transition peak (μ) on the E'' loss modulus plot. Because α and β transitions are so close to each other, it is however difficult to detect an additional peak and using
 5 multifrequency data is often required.

Glass transitions (α and μ) are not so frequency-sensitive than do secondary transitions (β). Thus, should the new glass transition (μ) be superimposed to the β transition at a f frequency, measurements at $10 \times f$ and $f/10$ allow to differentiate them. In that case where the system
 10 contains 14% of chp-chp-ndu, it was found to be more useful to conduct a high-frequency measurement.

Other measuring methods that are more difficult to carry out could help better characterize the phase separation:

- Solid NMR provides molecular mobility values. The presence of two
 15 phases results in two relaxation time distributions.
- The atomic force microscopy (AFM) may in some cases allow to detect a phase separation. The modulus difference between potential phases is nevertheless very small.
- The transmission electron microscopy (TEM) is the particularly
 20 recommended method which allows to detect phase separations, whatever macroscopic or nanoscopic in nature, thanks to a ruthenium oxide labelling.

In addition to the solubility parameters of the additives, other parameters may be employed in order to enhance the phase separation
 25 formation.

Lattice formation cinetics influence

To avoid any additive demixing (creation of size ranges in the order of the mm or above, that are visible to naked eye, showing a heterogeneous distribution and causing the material to become friable),
 30 polymerization conditions may be modified and the lattice formation kinetics may be accelerated.

Polymerization cinetics

In a first time, only the kinetics influencing parameters were modified and the monomer structure remained unchanged.

Catalyst level – Temperature

Gel time measurements have been conducted for the XDI/00NDI/3SH matrix, at 60°C and with different catalyst levels. The device used ("gel-timer") does measure the time that is necessary to block the punch oscillatory movement in the formulation.

An infrared spectroscopy follow-up provides a gel point around 60% conversion, in consistency with the theoretical value given by the following Flory and Stockmayers equation:

$$p_c = \frac{1}{\sqrt{f-1}}$$
 where p_c is the degree of conversion to the gel point and f the functionality of the multifunctional compound.

Theoretical values are $p_c=71\%$ for XDI/00NDI/3SH ($f=3$) and $p_c=58\%$ for XDI/50NDI/4SH ($f=4$).

The gel time does obey an inverse power law vs. catalyst level (figure 4). Thus, using 0.10% of catalyst instead of 0.01% causes the gel time to be divided by 15.

On the other hand, the medium temperature has a significant effect on the gelification: at 120°C and with no catalyst, the formulation turns to gel within 2h30, as opposed to more than 24h at 60°C (See table hereafter).

Temperature	Catalyst level (%)	Gel time
120°C	0	2h30
60°C	0	>24h
	0.01	2h30
	0.02	1h15
	0.05	0h30
	0.10	0h10

Gel time vs. catalyst level, at 60°C for the XDI/00NDI/2SH matrix

Polymerization cycle

It is possible to take advantage of the influence of the temperature on the polymerization reaction by varying the temperature - time cycle.

Instead of a long polymerization cycle (approximately 20h to reach

120°C), the gel point will preferably be reached more rapidly thanks to a short cycle, with a 2 hour-long increasing ramp up to 120°C, starting from the miscibility temperature of the additive in the monomers (start at 60°C in figure 5 as an example).

5 Use of prepolymers

Prepolymers were synthesized so as to accelerate the gelification.

The amounts were as follows:

- Isocyanate end group prepolymer (NCO): 1 thiol function (SH) for 8 isocyanate functions (NCO).
- 10 • Thiol end group prepolymer (SH): 1 isocyanate function (NCO) for 8 thiol functions (SH).

The development of NCO prepolymers requires special attention to ensure the reproducibility of the results, in particular to prevent any possible condensation reaction of the isocyanates in isocyanurates which
15 would add cross-linking points to the system as a consequence.

A gel permeation chromatography (GPC) assay conducted on two batches reveals in this regard a deviation concerning the NCO prepolymer weight distributions. The weights that are indicated in the table do not take the remaining free isocyanates into account, which have an elution
20 volume too similar to the residual volume.

The SH prepolymer does not require so much attention, this being confirmed by a good reproducibility between both GPC-analyzed batches.

Sample	M_n	M_w	$I = \frac{M_w}{M_n}$
NCO prepolymer, batch 1	1633	9360	5.7
NCO prepolymer, batch 2	1435	3781	2.6
SH prepolymer, batch 1	250	1099	4.4
SH prepolymer, batch 2	262	1046	4.0

25 GPC results, weights in polystyrene equivalent, for 2 XDI/50NDI/4SH prepolymer batches

(M_n : number average molecular weight; M_w : weight average molecular weight; I: polydispersity).

Gel time measurements reveal that in similar reaction conditions (catalyst, temperature), using prepolymers causes the gel time to be reduced by a factor of 2, making it very interesting for accelerating the matrix production.

- 5 In addition to using prepolymers, another catalytic system may be used as an initiator. This relies on a potassium isothiocyanate (KSCN) complexed with a crown ether. In such a case the gel time for a mixture made at the ambient temperature is less than 5 min and has a high exothermicity (above 120°C).

10 Preparation of XDI/50NDI/4SH prepolymers

Isocyanate prepolymer

Each of the (XDI, NDI) isocyanate monomers is divided in two parts, XDI-1 and XDI-2, and NDI-1 and NDI-2, respectively. Each of the parts is then blended according to the hereunder procedure.

15

Name	Weight (g)	mole number (mol)
XDI – 1	62.60	0.333
NDI – 1	62.60	0.304
4SH	27.43	0.071
XDI – 2	48.69	0.259
NDI – 2	48.69	0.236

Admixing thiol (4SH) with isocyanate mixture – 1 (XDI – 1 + NDI – 1).

Heating at 118°C and stirring for 2 hours.

Adding the isocyanate mixtures – 2 (XDI – 2 + NDI – 2).

- 20 Cooling to the ambient temperature.

Keeping under inert atmosphere (N₂, Ar).

Thiol prepolymer

Name	Weight (g)	Number of moles (mol)
4SH – 1	166.40	0.429
XDI	14.07	0.075
NDI	14.07	0.068
4SH – 2	55.47	0.143

The thiol monomer is divided in two parts, each having a different weight and being referred to as 4SH-1 and 4SH-2.

Mixing 4SH – 1 with (XDI+NDI) isocyanates.

Heating at 93°C and stirring for 4 hours.

- 5 Checking NCO peak disappearance using an IR spectroscopy.

Adding 4SH – 2 and cooling to the ambient temperature.

Results

Thanks to the polymerization reaction acceleration, the gel point is achieved more rapidly. It makes it thus possible to prevent a demixing
10 before the gel point, and thermoset antiplasticized plastic materials exhibiting a phase separation could be obtained.

For example, in the XDI/50NDI/4SH matrix:

- 8% chp-ch-u: demixes with the long thermal cycle; hardly diffusing as evaluated by visual examination with the short cycle, thus
15 demonstrating a phase separation.
- 10% ch-ch-tdedu: demixes with 0.02% catalyst, transparent with 0.07%.
- 18% chp-chp-ndu: totally, evenly opaque when the formulation includes the monomers, strongly diffusing but non opaque with the
20 prepolymers.

Dynamic mechanic analysis (DMA)

A new peak could not be evidenced for all diffusing systems. The samples however have not all been measured for various frequencies to decorrelate potential superimposed peaks.

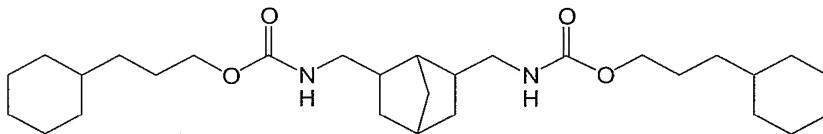
(XDI/50NDI/4SH matrix)

Additive	Level from which the material becomes diffusing in the slowest kinetic conditions	New transition DMA signature
ch-ch-tdedu	10%	YES
chp-chp-ndu	14%	YES
chp-chp-xdu	10%	YES
che-che-ndu	23%	YES
che-che-xdu	16%	NO
nm-nm-ndu	19%	NO
Ch-ch-tdedu + p-p-tdedu mixture	10%	NO
p-p-tdedSu	6%	NO
ch-ch-tdedSu	6%	NO
p-p-dtodu	16%	NO
ch-ch-dtodu	16%	NO
chp-ch-u	8%	NO

When there is a phase separation, the antiplasticizing effect is not so strong and does not enable any increase in the E' modulus as compared to the pure matrix. This is very probably due to the lower interaction between the additive and the matrix, needed for the phase separation.

As far as the chp-chp-ndu additive is concerned, the DMA-identified phase separation resulting in diffusing lenses was further characterized by means of a transmission electron microscopy, with 75 nm inclusions.

The chp-chp-ndu additive:



was found to be especially interesting.

It produces a DMA visible phase separation creating hardly diffusing lenses. Using the prepolymer and catalytic system thereof may be advantageous to obtain transparent materials.

The ch-ch-tdedu additive is interesting as well, as it is transparent with a nanophase separation as evidenced by a transmission electron microscopy (phase typical size is less than 20 nm). Toughness measurements have been carried out again with many different incorporation rates and have been gathered in the table of the section called "toughness measurements".

10 Toughness

The toughness of some formulations was evaluated by a three-point bend fracture in notched specimens.

Toughness measurements

Linear elasticity fracture mechanics criteria

15 The linear elasticity fracture mechanics applies to materials obeying the Hooke's law (proportional relationship between applied stress and strain) when applying a stress onto the notched specimen (in our assay: mode I, tension crack opening). In this context, measuring two interdependent measurable variables enables to characterize the fracture mechanics:

- 20 • G_{Ic} : fracture energy (energy needed to initiate crack propagation)
 - K_{Ic} : fracture toughness (crack initiation strength of the material)
- with

$$G_{Ic} = \frac{K_{Ic}^2}{E} \text{ in case of plane stress, and } G_{Ic} = \frac{K_{Ic}^2 \cdot (1 - \nu^2)}{E} \text{ in case of plane strain}$$

25 **Experiment procedure**

Fracture tests were conducted on 3 point-bend specimens with an Instron 4301 apparatus (measures at 20°C – in an air-conditioned room).

Specimens to be used for fracture tests as illustrated in figure 6, were cut from 6 mm thick small disks to have a size in accordance with

what Williams recommended in his experiment procedure¹. In a first step, the specimens were pre-cut with a 0.5 mm thick cutter, then annealed at 120°C for 2 hours. Finally, a V-notch was made using a razor blade as a pre-notch ground, by means of a guillotine system.

5 Criteria concerning specimen geometry and notching must be strictly met so as to test the specimen in maximal brittleness conditions by applying formulas for K_{Ic} and G_{Ic} .

In the present case $B=6$ mm, $W=12$ mm.

Calculation of fracture measurable variables

10 K_{Ic} is experimentally determined basing on following equation:

$$K_{Ic} = f(\alpha) \times \frac{P_{max}}{BW^{1/2}}$$

where B and W correspond respectively to the thickness and the height of the specimen.

a corresponds to the depth of the notch (notch + pre-notch).

15 P_{max} corresponds to the maximum load encountered during the fracture test.

$$\alpha = \frac{a}{W}.$$

f is a geometric factor for a specimen having such geometry expressed by following equation:

$$20 \quad f(\alpha) = 6 \alpha^{1/2} \frac{1,99 - \alpha(1 - \alpha)(2,15 - 3,93\alpha + 2,7\alpha^2)}{(1 - 2\alpha)(1 - \alpha)^{3/2}}$$

G_{Ic} is experimentally determined as follows:

$$G_{Ic} = \frac{U_i}{B W \Phi(\alpha)}$$

where U_i is the area under the force vs. displacement curve to P_{max} .

25 Φ corresponds to a geometric factor:

$$\Phi(\alpha) = \frac{\Theta + 18,64}{\frac{d\Theta}{d\alpha}}$$

with

¹ Williams J.G., EGF Task Group on Polymers and Composites, A Linear Elastic Fracture Mechanics (LEFM) standard for determining K_{Ic} and G_{Ic} for plastics (1989)

$$\left\{ \begin{array}{l} \Theta(\alpha) = \frac{16\alpha^2}{(1-\alpha)^2} (8,9 - 33,717\alpha + 79,616\alpha^2 - 112,952\alpha^3 + 84,815\alpha^4 - 25,672\alpha^5) \\ \frac{d\Theta}{d\alpha}(\alpha) = \frac{16\alpha^2}{(1-\alpha)^2} (-33,717 + 159,232\alpha - 338,856\alpha^2 + 339,26\alpha^3 - 128,36\alpha^4) + \\ \frac{32\alpha}{(1-\alpha)^3} (8,9 - 33,717\alpha + 79,616\alpha^2 - 112,952\alpha^3 + 84,815\alpha^4 - 25,672\alpha^5) \end{array} \right.$$

Results of the measurements

These results include the results as mentioned in table I for
 5 XDI/50NDI/4SH, except those with an asterisk.

Sample	T _g (max tan δ) °C	DMA revealed μ transition	Diffusing material	K _{Ic} (MPa.m ^{1/2})	G _{Ic} (kJ.m ⁻²)
XDI/50NDI/4SH pure matrix	100	-	-	0.64	0.12
1/17 chp-ch-u (4%)*	82	no	no	0.67	0.15
1/8 chp-ch-u (8%)	106	no	Yes	0.67	0.15
1/5 nm-nm-ndu (20%)	100	no	Yes	0.71	0.15
1/6 pp-ch-u (10%)	86	no	No	0.73	0.14
1/2.5 pp-ch-u (21%)*	-	no	No	0.72	0.18
1/4 pe-pe-ndu (21%)	78	no	No	0.73	0.18
1/9 ch-ch-tdedu (10%)	102	yes	No	0.76	0.17
1/4 pe-pe-xdu (21%)	70	no	No	0.96	0.29
1/6 chp-chp-xdu (17%)	100	yes	Yes	0.86	0.24
1/8 chp-chp-ndu (14%)	104	yes	Yes	1.15	0.43
1/6 chp-chp-ndu (18%)	104	yes	Opaque	1.82	1.76
1/9 ch-ch-tdedu (10%)	102	yes	no	0.85	0.23
1/6 ch-ch-tdedu (14%)*	97	no	no	0.90	0.20
1/4 ch-ch-tdedu (20%)*	92	no	no	0.90	0.21

The results demonstrate the efficiency of the additives, especially of the
 10 chp-chp-ndu additive, for reinforcing the material. They show especially
 an increase in the energy release rate G_{Ic} as compared to the pure matrix.

As regards the ch-ch-tdedu additive, at 10%, the μ transition expressed as a shoulder in alpha main transition. Any μ transition could not be observed with high incorporation rates because the alpha and beta transitions are excessively close to each other.

5 The most promising chp-chp-ndu-containing materials despite diffusion were subsequently tested as to their impact resistance.

Impact resistance

10 The fracture energy for lenses was tested according to the FDA ophthalmic glass impact resistance standard. This assay consists in dropping a ball weighing 16 g from a 127 cm height in the centre of a convex face of a lens, corresponding to an energy of 200 mJ.

To measure the fracture energy for ophthalmic lenses, balls are dropped with an increasing energy in the centre of a lens until a starred crack occurs or until it comes to the point of bursting. The lens fracture energy 15 is then calculated.

Sample shape: concave lens, dioptries -2 , centre thickness: 1.55 mm.

Two materials were tested:

- XDI/50NDI/4SH pure matrix
- 14% chp-chp-ndu-loaded matrix

20 The correlation is good between the results concerning toughness and impact resistance, despite strongly scattered data for the material containing the additive. The impact resistance is therefore improved by the additive.

Sample	Fracture energy	K_{Ic} (MPa.m ^{1/2})	G_{Ic} (kJ.m ⁻²)
XDI/50NDI/4SH matrix	2400 mJ	0.64	0.12
XDI/50NDI/4SH + 14% chp-chp-ndu	4300 mJ (very scattered)	1.15	0.43